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The strength competition effect at different strain rates

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Abstract

The dynamic characterization of materials under intermediate and high strain rates is fundamental to understand the material behaviour in case of dynamic loadings. In this study dynamic tests of rocks in compression and splitting by the Kolsky method and its modification were analysed. The time dependence of the critical stress can predict by the incubation time of fracture criterion and these dependencies turned out to be in good agreement with experiments.

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Keywords: Dynamic loading, strength, incubation time;

1. Introduction

In selecting a material for construction is usually guided by the values of mechanical parameters obtained in quasi-static tests. For example, the strength of various buildings and structures has been defined according to the principle of the limiting force field for many years. Construction material is selected based on its ability to withstand a certain stress. There is a set of standards governing the determination of the ultimate strength of the material under quasi-static tension, compression, bending, etc. However tests of the strength of these materials under dynamic loading conditions show a essential difference in the dynamic strength characteristics of comparison with data of quasi-static tests. The dynamic characterization of materials under high loading rates is fundamental to understand the material behaviour in the case of dynamic events. The dynamic mechanical properties are very different from those exhibited in quasi-static conditions. In addition, a wide range of external loads could occur a strength inversion

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effect when take place change of the dominant strength between the two materials. A material, which has lower strength compared to another material in quasi-static tests, can have greater strength under dynamic loading a material may have a lower dynamic strength for a high static strength compared with other material.

Using the incubation time fracture criterion and experimental results for different materials were obtained some examples with the strength inversion effect characteristics of strength. The dynamic characterization was carried out by means of traditional Split Hopkinson Pressure Bar (SHPB) placed at the Laboratory of Dynamic Investigation of Materials of Nizhny Novgorod.

2. Experimental and analytical details

Progress in this area associated with the split Hopkinson bar (SHB). The experimental method originally proposed by Kolsky (1949) is today one of the most thoroughly developed and verified methods for obtaining the dynamic strain curves for materials. In recent decades many efforts were undertaken to develop experimental studies and new set-ups in order to analyse dynamic behaviour of different materials. For example, in work performed by Goldsmith and Sackman (1973) Kolsky method was used for some rock. In this work we show good compliance with the experimental method and theoretical investigation.

Dynamic compressive and splitting tests were performed in the Laboratory of Dynamic Investigation of Materials in Nizhny Novgorod by means of a SHPB shown in Fig. 1.

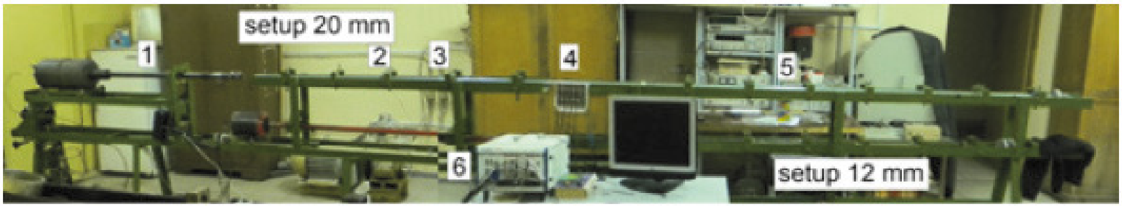

Fig. 1. Experimental apparatus realizing SHPB for compressive and splitting tests.

The experimental set-up consists of a compact gas gun (1), incident (2) and transmitter (5) steel (or duralumin) pressure bars with the specimen (3) sandwiched between them. Power supply and calibration of strain gauges was produced by an original scheme (4). In order to record the electrical signals from strain gauges, a multichannel digital oscilloscope (6) was used. The diameters of striker as well as pressure bar are 20 mm. The incident bar length was 1 m, while the length of the transmitter bar was 3 m in order to provide correct registration of possible additional cycles of loading during the experiment Rodriguez (1994).

The classical Kolsky scheme is used for compression tests. For dynamic tensile test, the modified Kolsky scheme – the Brazilian test is used. Splitting test disks is one of the available methods to measure the tensile strength of brittle materials (Bragov, 2001). Due to the stress-state of the disk, the failure is caused by tension when the tensile stresses reachs the tensile strength of the material at the diametric loading plane.

This article presents some results of dynamic compression and splitting tests of rocks: gabbro and two type of marble (Koelga and Pervouralsk). Gabbro - one of the most common intrusive rocks. This breed is composed of plagioclase and clinopyroxene in roughly equal proportions. Gabbro-diabase rock is the basic structure, with a massive texture, fine-medium grained, without cavities and irregularities uniformly painted in dark gray. Test specimens were taken from Drugoretskoe field (Republic of Karelia). Marble - durable, capable polished limestone. Marble deposits found in various parts of Russia. Above all, more than 20 fields, located in the Urals, but the stone is mined only from 8 deposits. Marble Koelga and Pervouralsk taken respectively from Chelyabinsk and Sverdlovsk region of Russia. Material properties are given in Table 1.

Test specimens in the form of rectangular parallelepipeds sawn diamond cutting discs from flat slabs of 20mm thick and length dimensions 20x20x10mm, 20x20x20mm, 20x20x30mm, 30x30x20mm. Samples of the first two sizes are used for high-speed tests on a simple compression and splitting under compression (Brazilian test). Samples with a size 20x20x30mm are mainly used for static testing in compression. Samples with a size 30x30x20mm - for dynamic tests with compression and splitting under compression in the quasi-static and dynamic tests.

Table 1. Material properties

	Gabbro-diabase	Marble Koelga	Marble Pervouralsk
Young's modulus, MPa	91550	56000	56000
Average Compressive strength, MPa	215	45	35
Average Tension strength, MPa	17,5	5,5	4,5

Static and dynamic loading tests were analyzed using unified criterion. In the case of slowly applied load there exists the threshold value of load amplitude. In the case of a very short durations the strength characteristics of materials are considerably different from those obtained in the case of quasi-static testing. But this can be explained by the circumstance that the time of loading is of the same order as the typical time of certain processes at the micro-level. The criterion of fracture based on the concept of incubation time, proposed by Morozov (2000), Petrov (2013), Evstifeev (2012), Petrov (2013), makes it possible to predict the unstable behavior of the dynamic-strength characteristics observed in experiments on the dynamic fracture of solids. The fracture criterion can be written in the following general form:

$$\frac{1}{\tau}\int_{t-\tau}^{t}\sigma(s)ds \le \sigma_{st} \tag{1}$$

where τ is the incubation time, σ_{st} is a strength (tensile, splitting and compression) for quasi-static loading and $\sigma(t)$ is the applied stress which for $t<0$ is supposed to be zero. The instant of fracture t* corresponds to the earliest realization of equality in Eq. (1) or, in the general case, violation of this condition.
For our tasks (uniaxial extension) take stress $\sigma(t)$ in this form

$$\sigma(t) = \dot{\sigma}tH(t) \tag{2}$$

where $H(t)$ is a Heaviside step function, $\dot{\sigma}$ is the rate of growth of stress (supposed to be constant). We substitute this function into the stress criterion Eq. (1) and to find the value of the time to failure t*

$$t^* = \begin{cases} \frac{\tau}{2} + \frac{\sigma_{st}}{\dot{\sigma}}, t^* \ge \tau \\ \sqrt{\frac{2\sigma_{st}\tau}{\dot{\sigma}}}, t^* < \tau \end{cases} \tag{3}$$

which gives the following expression for the limiting stress

$$\sigma^* = \sigma(t^*) = \begin{cases} \sigma_{st} + \frac{\tau\dot{\sigma}}{2}, t^* \ge \tau \\ \sqrt{2\sigma_{st}\dot{\sigma}\tau}, t^* < \tau \end{cases} \tag{4}$$

The general concept of incubation time works in both compressive and tensile cases, but the set material constants must be determined for compression and tension separately. The problem of testing the dynamic strength properties of materials may be associated with the determination of the incubation time parameter. The incubation time of fracture τ can be determined by the iterative procedure optimal fitting calculated values σ^* to the experimental points.

According to this approach the incubation time parameter and the static critical stress (for tension or compression) of a material represent the set of fixed material characteristics allowing one the calculation of critical loads in a wide range of strain rates. The dynamic strength of the material is determined by the incubation time of the destruction.

3. Results

Experiments for tension were completed like a model "Brazilian tests", but samples were in the form of rectangular parallelepipeds. Experimental schemes on Fig. 1. Samples were made from flat slabs of marble Koelga and Pervouralsk, gabbro-diabase.

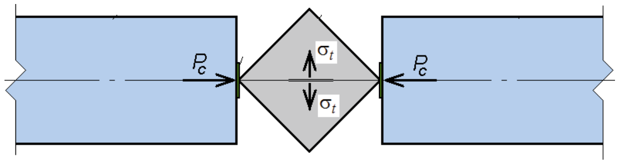

Fig. 1. Experimental scheme for splitting tests.

For tensile stress formula in the form

$$\sigma_t = 0.5187 \frac{P_c}{b\,h} \quad (3)$$

where b and h - dimensions of the sample, P_c – the longitudinal force in the gauging rods, is determined by indications on the support rod. The maximum value of the tensile stress is the required tensile strength of stone.

On Fig. 2 illustrate the effect of the dynamic tensile strength. Points show the experimental data. The curves show the theoretical line constructed by the formula (1) with parameters τ = 1µs, σ_{st}=5.5MPa for marble Koelga, τ = 1.7µs, σ_{st}=4.5MPa for marble Pervouralsk and τ = 0.7µs, σ_{st}=17.5MPa for gabbro-diabase.

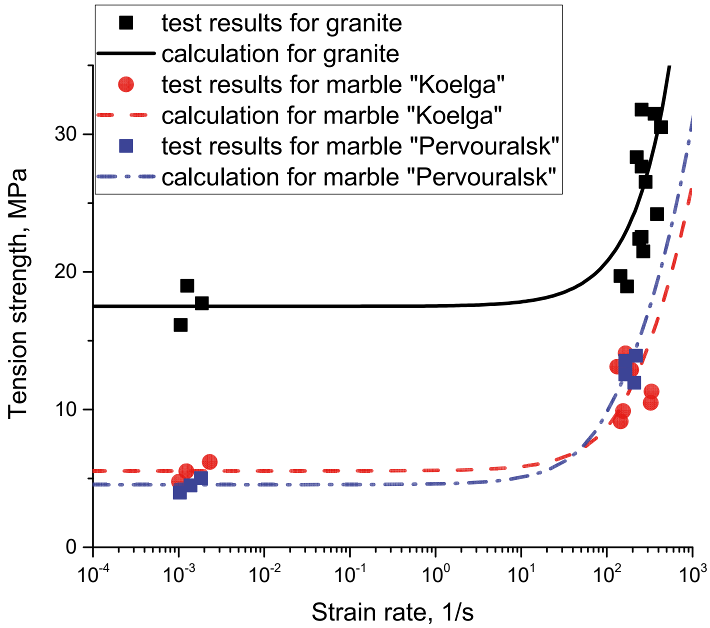

Fig. 2. Dynamic split critical stress of rocks vs average strain rate.

The dynamic split critical stress of rocks in the studied range of strain rate increases, and can be effectively predicted by the incubation time criterion. The incubation time of fracture it is dynamic strength. Analyse of results showed that the marble Pervouralsk has a lower static strength of the materials, but one has a higher dynamic strength (the icubation time parameter) than the marble Koelga. The granite samples have greater strength than all types of marble.

For compression tests were carried out standard experiments use the classical Kolsky scheme. On Fig. 3 shows the effect of the dynamic compression strength. Points show the experimental data. The curves show the theoretical line constructed by the formula (1) with parameters τ = 2.8μs, σ_{st}=45MPa for marble Koelga and τ = 3.9μs, σ_{st}=35MPa for marble Pervouralsk and τ = 6 μs, σ_{st}=215 MPa for gabbro-diabase. We can also see the good compliance of the theoretical approaches and experimental data is a huge difference between the strength of marble and granite.

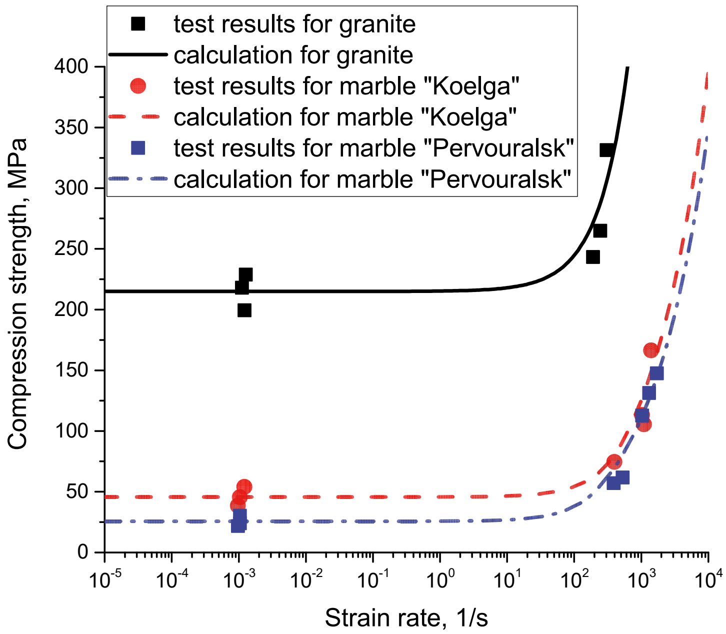

Fig. 3. Dynamic compression critical stress of rocks vs average strain rate.

4. Conclusion

The study of dynamic mechanical properties of the rock materials was performed using the Kolsky method and its modification for dynamic splitting (the Brazil test). Rock tensile and compression strength is strain rate dependent. It has been verified for the marble Koelga, Pervouralsk and granite (gabbro-diabase). The results show the non-linear relationships between the strength and strain rates.

For different types of marble we can see the strength inversion effect of load-carrying capacity of materials at different strain rate under compression. The strength inversion effect means that in spite of the fact that static strength of one material is smaller than that of another one, its dynamic strength may be essentially higher.

The analysis was conducted based on the incubation time approach, which allows one to separate static strength and dynamic strength. As the incubation time is a material parameter we can estimate and compare the load-carrying capacity of materials in a wide range of loading rates.

Thus, one of the main problems in testing of the dynamic strength properties of rocks may be connected with the measurement of parameters of the incubation time. Studies of strain rate features using incubation time approach provide an effective opportunity to examine the fracture process that is important for predicting critical parameters of external action in a wide range of loading conditions.

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